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Estimating the water needed to end or ameliorate the drought in the Carpathian region

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Abstract

A drought severity climatology for the Carpathian Region has been produced using the self-calibrating Palmer Drought Severity Index (Sc-PDSI) for the period 1961–2010. Using the Sc-PDSI and the assumptions of the Palmer Drought Model (PDM) the precipitation required for drought termination (when Sc-PDSI reaches −0.5) and amelioration (when Sc-PDSI reaches −2.0) are computed for periods of 1, 3 and 6 months. We discuss the reduction of the uncertainty in the determination of the beginning and ending of drought conditions and provide a quantitative measure of the probability that any drought could be ameliorated or terminated. We present how the spatial variability of the amount of water needed for drought recovery and the climatological probability of receiving that amount of water is determined by the local conditions against the general climate characteristics of a small area such as the Carpathian Region. Regionally, the Pannonian Basin, the Transylvanian Plateau and the external Carpathians foothills and plains in the southern and eastern part of the region require the highest quantity of precipitation to recover from a drought while having the lowest climatological probabilities for such amounts of rainfall. High precipitation amounts over the North and northwest part of the region result in higher soil moisture supplies and higher climatological probabilities to end a given drought event. Moreover the succession and/or predominance of particular types of general atmospheric circulation patterns produce a seasonal cycle and inter-annual variability of precipitation that is quantitatively reflected in the excess of precipitation above normal required for drought recovery. Overall, the results of this study provide an overview on the chances of recovery from a drought period with moderate or severe drought and present information useful in decision making in water and drought management.

1 Introduction

Drought is one of the most far-reaching natural and socio-economic disasters (WMO/UNCCD/FAO/UNW-DPC, 2013). Traditionally, the acknowledgement and attempts to manage droughts were mostly orientated towards crisis management, while little attention has been given to pro-active drought risk management. More recently, European as well as international policies and initiatives have highlighted the need for a more pro-active, risk-based management of droughts. Examples are the requirement for the set-up of River Basin Management Plans, including Drought Management Plans under the European Water Framework Directive (WFD), the High Level Meeting on National Drought Policies (HMNDP, http://www.hmndp.org), or the Integrated Drought Management Programme (IDMP, http://www.droughtmanagement.info/) established by the World Meteorological Organization (WMO) and the Global Water Partnership (GWP) in 2013.

An essential element in risk management is the reduction of drought impacts (i.e. mitigation) based on an assessment of the cost of damages associated with droughts as compared to the costs for efficient early warning and preparedness, including the adaptation to climate change. Drought as a natural hazard has been the subject of a great number of studies, focusing on the definition of drought and the development of drought indicators (e.g., Palmer, 1965; McKee et al., 1993; Wells et al., 2004; Vicente-Serrano et al., 2010b) as well as on drought assessment and monitoring (e.g., Briffa et al., 1994; Guttman et al., 1998; Lloyd-Hughes and Saunders, 2002; Dai et al., 2004; van der Schrier et al., 2006; Dai, 2011). However, little attention was given to the analysis of probabilities that a given drought (and its impacts) could be ameliorated or terminated through adequate rainfalls. The number of studies addressing the drought recovery topic are few (Karl et. al., 1986, 1987) and articles focused on drought as a natural hazard (Wilhite et al., 2005, 2000a) as well as reports on drought management and monitoring (e.g., WMO, 2006; IPCC, 2007; ISDR, 2007), address the subject only in a general manner.

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This paper provides a quantitative measure of the probability that any drought could be ameliorated or terminated over some defined period of time – using the assumption of the Palmer Drought Model (PDM) (Karl et al., 1987). The study was partially implemented in the framework of the CARPATCLIM project (http://www.carpatclim-eu.org). Within this project a consortium of meteorological services and environmental institutes of 9 countries of the region joined forces with the purpose of improving the availability and accessibility of quality controlled meteorological and climatological data. Based on the CARPATCLIM daily and monthly gridded data ($0.1^\circ \times 0.1^\circ$ resolution for the 1961–2010 period), a series of indicators were computed with the purpose of defining the climate characteristics of the region. Among them the Self-calibrating Palmer Drought Severity Index (Sc-PDSI), which was selected due to its ability to measure the intensity and severity of drought events (van der Schrier et al., 2006) and to quantify the impact of droughts on a wide range of economic sectors (it serves as a meteorological, hydrological and agricultural drought index, Karl, 1983; Karl and Knight, 1985). In addition, it can be used (following the assumptions of the Palmer Drought Model) to assess the chances of drought recovery. Despite its importance, quantifying drought recovery has not been examined yet, in the Carpathian region.

The Sc-PDSI is a drought indicator based on the principles of balance between moisture supply and demand. A series of articles have pointed out the assumptions, strengths and weaknesses of the Palmer Drought Model along with details on calculation procedures (Alley, 1984; Karl, 1987, 1986a, b; Wells et al., 2004; van der Schrier et al., 2006). Based on these considerations the precipitation needed to end or ameliorate a drought at a specific level of severity (Sc-PDSI ≤ -2, Sc-PDSI ≤ -3, Sc-PDSI ≤ -4), and the climatological probability that this precipitation could fall have been computed for time periods of 1, 3 and 6 months ahead. A spatial and temporal analysis of these results is presented, including information on the deviation (%) of the required precipitation from the normal annual rainfall cycle and an analysis of the months of the year with the highest/lowest probability for terminating a drought at different levels of severity.

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The paper is organized in 3 sections. Following the introduction, in Sect. 2 we detail the data and computation methodologies used in this study and in Sect. 3 we present the results of the spatio-temporal analyses. Final conclusions are then drawn in Sect. 4, followed by an Appendix where we detail the Sc-PDSI calculation.

2 Data and methodology

2.1 Data

The region covered by this study, depicted in Fig. 1, is centred on the Carpathian Mountains and the surrounding lowlands (17–27° E, 44–50° N). The data required to calculate the water needed to recover from drought events are reprocessed from the Palmer Drought Model used to compute the Sc-PDSI. The computation of the Sc-PDSI (Wells et al., 2004) is based on the moisture demand and supply (water-balance model) and takes into account precipitation, evapotranspiration and soil moisture conditions. The basic input data are the following:

- Gridded monthly precipitation (from the CARPATCLIM project at $0.1^{\circ} \times 0.1^{\circ}$ spatial resolution for the 1961–2010 period);
- Gridded monthly mean surface air temperature (from the CARPATCLIM project $0.1^{\circ} \times 0.1^{\circ}$ resolution for the 1961–2010 period) used to compute Thornthwaite's Potential Evapotranspiration – PET, (Thornthwaite, 1948);
- The Available Water Holding Capacity (AWC) of the soil, computed from the soil texture classes and soil profile depths in the European Soil Database (http://eusoils.jrc.ec.europa.eu/) and the Soil Geographical Database of Eurasia (Toth and Weynants, 2012). The AWC values per grid cell, shown in Fig. 2, are assumed to be constant over the considered period and calculated using the van Genuchten equation for which the parameters are obtained from the HYPRES pedotransfer class functions (based on the texture classes) (Wosten et al., 1999).

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In addition the climatic water balance was used (computed as a difference between gridded accumulated precipitations and potential evapotranspiration) together with 6 hydrological parameters of the soil water balance: recharge, runoff, and water loss from the soil and their potential values (used in the calculation of Palmer's constants to give the Climatically Appropriate for Existing Conditions for the specific location, i.e. the so called CAFEC precipitation).

Finally, gridded datasets of CAFEC precipitation ($\hat{P}$), the climate characteristic coefficient (K_i) and the moisture anomaly index (Z_i) (from the Palmer Drought Model) for the 1961–2010 period were used for the computation of the precipitation needed to end and ameliorate a drought. The climatological probabilities of receiving these precipitations were calculated using the probability density function and the cumulative probability function of the gamma distribution.

2.2 Computation methodologies

2.2.1 Sc-PDSI computation

Sc-PDSI is based on the Palmer Drought Severity Index (PDSI), first introduced by Palmer (1965), and originally computed on a monthly basis and modified by Wells et al. (2004). It measures the cumulative departure of moisture supply and demand. The supply in this model is the precipitation, the water demand is the potential evapotranspiration and the outputs are the actual evapotranspiration and runoff. Often discussed in other studies (e.g., Alley, 1984; Karl, 1986a; Guttman et al., 1992; Weber and Nkemdirim, 1998; Wells et al., 2004; Dai et al., 2004; Vicente-Serrano et al., 2010b) the strengths, weakness and differences of these two drought indicators will not be examined in this study. The major difference lays in the reduced frequency of extreme events of Sc-PDSI when compared with PDSI as an overall effect of the calibration based on the actual climatic characteristics of a given location that allows Sc-PDSI to be more comparable between different locations.

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A description of the modifications made to obtain Sc-PDSI is presented in, Appendix A.

2.2.2 Ending and ameliorating the drought

The Sc-PDSI$_i$ values and the assumptions of the Palmer Drought Model (PDM) were used for setting the theoretical basis of the calculation of precipitations needed to recover from the drought. The precipitations needed to end or ameliorate the drought are calculated rewriting PDM's equation used to compute the moisture anomaly index (Z_i), from:

$$Z_i = (P_i - \hat{P}_i)K_i \tag{1}$$

to $$P_i = \left(\frac{Z_i}{K_i}\right) + \hat{P}_i \tag{2}$$

where, P_i = precipitation needed to end or ameliorate the drought, $\hat{P}_i$ = CAFEC precipitation and K_i = the coefficient of climate characteristic.

However, before being able to compute P_i, Z_i has to be adapted to recovering drought conditions (end or ameliorate) and $\hat{P}_i$ has to be related with the Sc-PDSI$_{i-1}$ (of the previous month) as CAFEC precipitation (with its soil water balance variables) cannot be computed until the end of the month.

a. *The first step* represents the transformation of the moisture anomaly index (Z_i) from the self-calibrated drought severity formula in Eq. (3) into the moisture anomaly index needed to end the drought (Z_e) and the moisture anomaly index needed to ameliorate the drought (Z_a).

   $$\text{Sc-PDSI}_i = p\text{Sc-PDSI}_{i-1} + qZ_i \tag{3}$$

   From the PDSI severity classes (Palmer, 1965), adopted also for the Sc-PDSI (Table 1), it can be stated that a drought event ends when the Sc-PDSI increases

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above −0.5. Therefore, when the Sc-PDSI$_i$ in Eq. (3) is set to −0.5 and solving for Z_i – which now should be mentioned as the moisture anomaly index needed to end the drought (Z_e) – the new formula becomes:

$$Z_e = \left(\frac{-0.5}{q}\right) - \left(\frac{p}{q} \cdot \text{Sc-PDSI}_{i-1}\right) \quad (4)$$

Considering the same severity classes, it can be assumed that a drought is ameliorated when the Sc-PDSI reaches a value of −2.0. Applying the same hypothetical basis when trying to calculate the moisture anomaly index needed to ameliorate the drought (Z_a), the Sc-PDSI$_i$ in Eq. (3) is set to −2.0 and the formula becomes:

$$Z_a = \left(\frac{-2.0}{q}\right) - \left(\frac{p}{q} \cdot \text{Sc-PDSI}_{i-1}\right) \quad (5)$$

The q and p are weighted factors – computed at all the locations (grid points) – specific for the dry spells. They are site-dependent which make the Z_a and Z_e unique for every grid point. Moreover, these two formulas can be computed not only for different values of Sc-PDSI$_{i-1}$but also for periods of time longer than a month. Once these simultaneous equations are solved, moisture anomaly indexes needed to end (Z_e) or ameliorate (Z_a) a drought are computed for different Sc-PDSI$_i$ intensities and different time periods (1, 3 and 6 months in our study).

b. *The second step* is assigning values to the CAFEC precipitation ($\hat{P}_i$) in Eq. (2) since the balance of the demand and supply at the level of soil moisture is solved only at the end of the month. Once this balance reaches a deficit of water, the anomaly is reproduced at the level of the drought indicator in the next month. So, in order to supply the model with precipitations needed to recover the drought at the time when this anomaly happens, the values of CAFEC precipitations were regressed at the level of Sc-PDSI$_{i-1}$ for each month during a drought. In order to solve this relation $\hat{P}_i$ is linearly regressed against Sc-PDSI$_i$ at time $i-1$, $i-3$ and $i-6$. The new $\hat{P}_i$ can be called the CAFEC precipitation regressed, matching the time (month) when the drought indicator registers the drought event.

c. In the *third step* the precipitation needed to end or ameliorate the drought is computed as in Eq. (2), using the moisture anomaly index needed to end (Z_e) or ameliorate (Z_a) the drought and the regressed CAFEC.

2.2.3 Probability calculation

The climatological probability of receiving the amount of precipitations needed to end and ameliorate the drought was calculated using the Gamma distribution. The statistics were performed separately for each month and each location (grid point) on the basis of the entire 50 yr of available data (1961–2010). Input data were the computed precipitation needed to end or ameliorate the drought ($0.1^{\circ} \times 0.1^{\circ}$ resolution) in the next 1, 3 and 6 months and the actual gridded monthly precipitation ($0.1^{\circ} \times 0.1^{\circ}$ resolution) accumulated for the same time periods. The probability statistics should not be considered as a forecast. They represent a quantitative measure of the probability computed on the basis of past actual precipitation data. Practically, the *probability density function* (PDF) of the actual precipitation data is used to find the *cumulative probability* (CDF) of the precipitation needed to recover from the drought for the required month and temporal scale.

All the procedures followed in the calculation of the climatological probability of recovering from a drought are based on the processes used by Oeztuerk (1981) to compute the probability distribution for precipitation. In a *first step* the actual precipitation data on "moving windows" of 1, 3, 6 months are matched with the precipitation needed to recover from the drought in the next 1, 3 and 6 months. In a *second step* the cumulative probability (CDF) of the computed precipitation needed to end or ameliorate the drought is derived.

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3 Results

The spatial and temporal analysis of the results for precipitations needed to recover from a drought and their climatological probability is related to 3 levels of severity: moderate drought when $-3 <$ Sc-PDSI ≤ -2, severe drought when $-4 <$ Sc-PDSI ≤ -3 and extreme drought when Sc-PDSI ≤ -4, which are evaluated on a temporal window of 1, 3, and 6 months.

Previous studies of drought in the Carpathian region were based on the analysis of intensity, duration and spatial extent, either at national level (e.g., Palfai, 1990; Snizell et al., 1998; Szalai, 2000; Popova et al., 2006; Trnka et al., 2009; Cheval, 2013) or at inter-regional level (e.g., Bartholy et al., 2013; Spinoni et. al, 2013). Our results show that the incidence of drought in this region is rather high. During the period 1961–2010, every part of the region experienced on average between 0.5 and 4 to 6 drought months per year, (Sc-PDSI ≤ -2, Fig. 3 left). Moreover the incidence of extreme drought (Sc-PDSI ≤ -4) has an occurrence of 5 to 45 days per year for the same time interval as shown in Fig. 3, right.

3.1 Drought recovery and its temporal variability

As shown in the Fig. 4 the incidence of drought events (Sc-PDSI ≤ -2) is most pronounced during the early years of the 1960's, 1970's and 2000's, as well as during almost the entire decade of the 1980's and 1990's and more isolated in the years 1968, 2007 and 2009. One of the characteristics of these drought events is the strong prevalence (% from the area) of extreme droughts (Sc-PDSI ≤ -4) as compared to other severity levels. This can be seen especially in the years with the highest general incidence over the region: 1961, 1964, 1968, 1987, 1990, 1992, 1993, 2001–2003, 2007. For these cases most of the drought events happened either in the summer period (from June to August) or in the winter months (December to February), for a few cases drought occurred in October or March and April.

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As shown in Table 2 for selected drought events between 200 % to more than 480 % of the normal 1-monthly precipitation would have been required for recovery (i.e. bringing SC-PDSI to a level of −0.5). For a 3 month period, the percentage is reduced from 100 % to almost 230 % of the 3-monthly precipitation, and for a 6 month period still up to 50 % above the normal 6-monthly precipitation would have been required. To ameliorate a drought (i.e. reaching SC-PDSI of ≥ −2) smaller amounts of precipitation would be sufficient: 70–100 % above the normal precipitation in 1-month, 30–60 % in 3-months and less than 20 % in 6-months.

In order to get a better idea of the climatological probabilities to recover from such droughts, we analysed the first 25 most significant events (droughts occurring on > 75 % of the area) for different drought intensity levels. Figure 5 shows the required precipitation in per cent of the climatologically expected precipitation and the associated probabilities for different drought intensities and precipitation accumulation periods. It can be seen that a moderate severity droughts (−3 < Sc-PDSI ≤ −2) required between 110 and 550 % of the normal 1-monthly precipitation for recovery (top left), while for 3-months the range between 50 and 200 % and the values for 6 month are well within the climatologically expected. For the same drought cases, during the peak intensity of the drought (Sc-PDSI ≤ −4) the quantity of precipitation required, increased up to approximately 8 times above the normal 1 month precipitation, while for 3 month the values reach up to 300 %, only for the 6-monthly precipitation the required values are close to the climatologically expected (bottom left). Severe droughts (−4 < Sc-PDSI ≤ −3) would have been ended with rainfall between 2 to 7 times the 1 month normal precipitation and approximately 100 % of the 6 month normal precipitation (centre left).

Most of these values indicate the improbability of ending or ameliorating the drought, in a short period of time, as their climatological probability is (extremely) low. If we settle a limit of 50 % probability, above which the quantities of precipitation could be considered more likely than not (IPCC, 2007), none of the drought events could have been ended in the next month. However, a few of the moderate droughts (August 1990,

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December 1986, December 2000, January 1991) and of the severe droughts (July 1990, December 2000, January 1990) could have been ameliorated with 48 to 140 % above the normal precipitation in 1 month (top right). On the other hand in 6-months almost all drought events considered could most probably have been ended with 10 to 80 % above the normal precipitation (188 % for the extreme drought of April 1991). Only the severe drought in January and February 1964 and the extreme droughts in July 2007 could not have been ended even in 6-months, making them the most excessive droughts of the studied period in the Carpathian region. Nevertheless, they could have been ameliorated with 45 to 65 % above the normal 6 month precipitation. In 3-months, only one drought event of extreme intensity (July 1990, requiring 136 % above the normal precipitation), 12 events of the moderate and 6 events of severe droughts could have been ended with high probability. All the other events could only have been ameliorated with a range of 15 to 140 % (August 1992) above the normal 3-monthly precipitation.

3.2 Drought recovery and its spatial variability

PDSI originally was designed to measure the soil moisture departures as a difference between a climatological moisture supply which in our case is the actual precipitation and the precipitation needed to maintain a normal soil moisture level (CAFEC precipitation, Palmer, 1965). In this study other means of moisture supply such as precipitation in form of snow water equivalent are not considered. Since the regional spatial variation of precipitation in this region is mainly determined by the mountain orography and the large scale atmospheric processes (KEO; UNEP/DEWA, 2007), it is expected (in a temperate-continental climate) that moisture supply is more significant in the high altitudes while the moisture demand is higher in the low altitudes (higher rate of evapotranspiration due to higher temperatures). With increasing continental conditions from West to East and temperature decreasing from North to South, a higher moisture demand in the South and southwest and higher moisture supplies in the North, West and southwest parts of the region are expected. The annual cycles of the

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moisture supply and demand follow a continental pattern with a maximum of supply and demand at the beginning of the summer (May/June/July) respectively end of summer (July/August) and a minimum in the winter months (December/January/February).

Figure 6 presents the positive deviations (in per cent) from normal precipitation needed to recover from a drought. The Pannonian Basin, the Transylvanian Plateau and the external Carpathians foothills and plains in the southern and eastern part of the region require the highest relative quantities of precipitation to recover from a drought. In these regions, moderate droughts and extreme droughts needed between 250 and 300 % (sometimes up to 600 %) above normal precipitation to end a drought, a decrease being noticed with increasing altitude. The topographic pattern is lost when the moisture supply is required for a larger time window. This is due to the general climate characteristics that overwrite the variability introduced by the local physical conditions. Also, the longer time intervals require less relative amounts of precipitation to recover from droughts (i.e. from 20 up to 40–60 % for all the drought intensities).

Figure 7 shows the corresponding probabilities. The probability of ending or ameliorating an extreme drought (Sc-PDSI ≤ -4) or a severe drought ($-4 <$ Sc-PDSI ≤ -3) in 1 month is low (< 8 %), showing the improbability of recovering the high intensity droughts in such a short time interval. The probability remains below 20 % even for the moderate droughts. For a 3 month period the probability of ending a drought is increasing from below 10 to 40 % for the extreme droughts, but is still unlikely (< 33 %) or about as likely as not (33 to 66 %). More likely, with a probability of 60 to 80 % a moderate drought could be ended over almost the entire region in the 3 month time interval. Once we advance to the 6 month interval, all droughts, indifferent of their intensity level, move from likely (> 66 %) to virtually certain (> 99 %) to be ended.

For both the required precipitation and the probabilities of recovery a spatial pattern linked with the atmospheric circulation patterns responsible for the climate variability in the Carpathian region can be noticed. The southern and southwestern Carpathians and the western Carpathians act like a barrier for the main sources of moisture (Mediterranean and North Atlantic air masses; Busuioc and von Storch, 1996; Busuioc,

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2001). This systems are causing high precipitation amounts over the southwestern, northern and northwestern part of the region, which produce high moisture supply and higher climatological probabilities when affected by drought events and less precipitation in the Carpathian foothills and plains in the southern and eastern part of the region, the Pannonian Basin and the Transylvanian plateau, causing low moisture supply and lower climatological probabilities.

The succession, intensity and the predominance of these air masses lead to a seasonal variability of the precipitation needed to recover from a drought and their climatological probability. The soil moisture supply and demand follow the annual cycle of precipitation and temperature which is reflected at the level of the month with the highest and lowest probabilities of recovering from a drought.

In almost the entire Carpathian region, the preferred months for ending a drought event are the months of May and June as in Fig. 8, corresponding with the peak of the annual precipitation cycle for most of the Carpathian region. The least preferred months for ending a drought are the months of January and February, corresponding with the months of the annual precipitation cycle. This situation can be observed in Fig. 8 where we present the months with the highest and lowest probability for ending droughts at different intensity during the next month in Fig. 8a, next three months in Fig. 8b and next six months in Fig. 8c.

Moderate drought events in April appear to have the highest probability for being ended in the next month. Also, severe and extreme droughts in April and May (for North and northeastern regions) are characterized by highest probabilities of being ended in following month. The late summer (July, August) and early autumn (September, October) drought events are ended with highest probability in the South, West and northwestern parts of Carpathian region as seen in the Fig. 8a, top.

In Fig. 8b top, we show that the drought events with the highest probability of being ended in 3 months are the droughts from the end of winter (January and February) in the West, South and northwestern regions and spring droughts (from April to May) in North and northeastern regions, especially for the extreme droughts. The late autumn

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drought events (October, November) present the highest probability of being ended in the next 6-months as seen in Fig. 8c, top.

Concerning the lowest probabilities for ending a drought event, the worst months for ending the droughts are the winter months, corresponding with the driest period of the annual precipitation cycle of the Carpathian region. This makes drought events between October (in the North, northeast area of the Carpathian region) and February (in the southern and eastern part of the region and Pannonian Basin) the least probable to be ended in the next month as seen in the Fig. 8a, bottom.

In Fig. 8b bottom, we show that the drought events with the lowest probability of being ended in 3 months are the droughts from the December in the North and northeastern regions and autumn droughts in the other regions.

The least probable to be ended in the next 6 months are the droughts that occur after or during the peak of the annual precipitation cycle (June, July, August), especially in the South and southwestern regions while the winter droughts are the least probable to be ended in the North and northeastern part of the region as seen in Fig. 8c.

This drought analysis reveals that the possible impact of droughts could be major especially because the agriculture is a major economic sector in the Carpathian countries (KEO; UNEP/DEWA, 2007). Moreover the main agricultural crops in the Carpathian region are winter wheat, maize and potatoes (KEO; UNEP/DEWA, 2007), which are highly vulnerable to droughts throughout the whole year. Therefore information on ending or ameliorating the droughts, climatological probability that the droughts could be recovered and the seasonal analysis of drought occurrence could be useful in decisions concerning the water and agricultural resources management.

4 Conclusions

The main characteristics of the spatial and temporal variability of precipitation needed to end or ameliorate a drought in the Carpathian region are presented in this study. Sc-PDSI was used as a drought indicator for the region and the Palmer Drought Model

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assumptions were considered for the theoretical basis to calculate moisture supply and demand. The incidence of drought in the region is considerable. During the study period (1961–2010) the region experienced, on average, drought events from at least 0.5 months to 4 to 6 months per year for moderate droughts and from 5 to 45 days per year for extreme droughts.

The amount of precipitation needed to end a drought in the next month, reached, on average, between 200 and 480 % above the normal 1 month and up to 50 % above the 6 month total of the normal precipitation. It was also shown that most of the drought events, no matter their intensity, are extremely unlikely (< 5 %) to be ended in the next month.

Regionally, the Pannonian Basin, Transylvanian Plateau and the external Carpathians foothills and plains in the southern and eastern part of the region require the highest quantity of precipitation to recover from a drought, corresponding to the lowest climatological probabilities. High precipitation amounts over the North and northwestern part of the region are causing higher moisture supply and higher climatological probabilities when affected by drought events. In almost the entire Carpathian region the best months for ending a drought event are the months of May and June, corresponding with the peak of the annual precipitation cycle for most of the Carpathian region and the worst months are the months of December and February corresponding to the driest period of the annual precipitation cycle.

Appendix A

Sc-PDSI calculation

The computation of the Self-calibrating PDSI was done in 4 steps: (a) computation of the soil water budget (Thornthwaite's method, 1948), (b) normalization with respect to demand, (c) normalization with respect to location and (d) computation of the drought severity.

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a. *Computation of the soil water budget* was done considering the following assumptions: the soil is divided in two layers, the AWC value is site dependent – representative of the soils type, the top layer contains 25 mm of available moisture at field capacity, the moisture stored in the soil layers changes according to the priority conditions imposed by the top layer on supply and demand. Rainfall surplus is first added to the top layer until this layer is full and only then it passes to the second layer while on the other hand moisture is withdrawn from the top layer first, before removing from the second soil layer.

   Following these rules eight hydrological parameters of the water balance are computed: the actual evapotranspiration (ET), the soil water recharge (R), the runoff (RO), the water loss from the soil (L) and their potential values used in the calculation of Palmer's constants to define the Climatically Appropriate for Existing Conditions (CAFEC) precipitation. By dividing the mean actual quantity by the mean potential quantity, coefficients defining the usual climate for a specific location were obtained (for evapotranspiration – α, recharge – β, runoff – γ, and loss – δ) as in Eq. (A2). The four coefficients are determined for each of the 12 months. The mean of the actual and potential quantities were computed over a baseline equal to the data period available (1961–2010).

b. *Normalization with respect to demand* (or moisture departure for the month – D) was calculated by subtracting from the normal precipitation the amount of precipitation needed to maintain a normal soil moisture level (CAFEC precipitation – $\hat{P}$, computed from the potential values of the water balance and their coefficients):

$$D = P - \hat{P} = P - (\alpha_i PE + \beta_i PR + \gamma_i P\mathrm{RO} - \delta_i PL) \quad \text{(A1)}$$

   where, D = moisture departure for the month, P = actual precipitation, $\hat{P}$ = CAFEC precipitation, α, β, γ, δ = water-balance coefficients computed as:

$$\alpha = \overline{\mathrm{ET}}_i/\overline{PE}_i, \quad \beta = \overline{R}_i/\overline{PR}_i, \quad \gamma = \overline{\mathrm{RO}}_i/\overline{P\mathrm{RO}}_i, \quad \delta = \overline{L}_i/\overline{PL}_i \quad \text{(A2)}$$

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where, ET, R, RO, L are the evapotranspiration, recharge, runoff, and soil moisture loss. $\overline{PE}$, $\overline{PR}$, $\overline{PRO}$, $\overline{PL}$ are their potential values, the bars indicate the average value and i ranges over the months of the year.

c. *Normalization with respect to location* was done by converting the moisture departure for the month (D) into an indicator of moisture anomaly (Z_i) by multiplying the moisture departure with a climatic characteristic coefficient (K). This is the point where the Sc-PDSI becomes different from the PDSI. The purpose of the climatic characteristic, K, is to adjust the value of PDSI according to the tails of its distribution in order to allow for an accurate comparison of PDSI values over time and space. Practically, the values of every location (pixel in this case) and each value of PDSI_i were weighted according to the 2nd and 98th percentile of the PDSI and compared with the expected −4.0 and +4.0 calibration:

$$K = \begin{bmatrix} \frac{-4.0}{\text{PDSI}_{2\text{nd}}} K', \text{ if } D < 0 \\ \frac{4.0}{\text{PDSI}_{98\text{th}}} K', \text{ if } D \geq 0 \end{bmatrix} \tag{A3}$$

where $\text{PDSI}_{2\text{nd}}$ and $\text{PDSI}_{98\text{th}}$ are the 2nd and 98th percentile of the PDSI distribution computed using K':

$$K'_i = 1.5\log_{10}\left[\left(\frac{\overline{PE} + \overline{R} + \overline{\text{RO}}}{\overline{P} + \overline{L}} + 2.8\right)\overline{D}^{-1}\right] + 0.5 \tag{A4}$$

where, $\overline{D}$ = average absolute value of the moisture departure and $\overline{PE}$, $\overline{R}$, $\overline{\text{RO}}$, $\overline{P}$, $\overline{L}$ are the parameters of water balance values of evapotranspiration, recharge, runoff, precipitation and loss.

Using the climate characteristic coefficient (K) and the moisture departure (D) for the month i, the moisture anomaly index is computed as:

$$Z_i = D_i \cdot K_i \tag{A5}$$

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d. *Computation of drought severity*. Once Z is computed for the month i, the computation of *the drought severity* begins by relating the previous month's PDSI_{i-1} with the current moisture anomaly Z_i. The weights assigned to these two components are given by the duration factors (p and q):

$$\text{PDSI}_i = p\text{PDSI}_{i-1} + qZ_i \quad \text{(A6)}$$

Differently from the original computation (the original PDSI is computed using the duration factors $p = 0.897$ for PDSI_{i-1} and $q = 1/3$ for Z_i) the Sc-PDSI duration factors for wet and dry conditions are computed separately, as it is assumed that different locations have different sensitivities to precipitation events. These duration factors (p and q) were computed using the least squares method for both extremely wet and extremely dry conditions, separately. Practically the accumulated Z_i was regressed against its duration (months) taking into account the most extreme drought/wet spell as shown in Fig. A1.

Extremely wet/dry spells are defined, in this study, as events with duration greater or equal to 3 consecutive months and with the highest intensity of Z_i (less/higher than 0.05/0.95 percentiles of accumulated negative/positive Z_i values are omitted). Once the intercept of the extreme wet/dry spells were computed, 2 sets of p and q (for dry/wet spells) were calculated as follows:

$$p = (1 - m/(m + b)) \quad \text{(A7)}$$

$$q = C/(m + b) \quad \text{(A8)}$$

where, m = slope, b = intercept of the extreme wet/dry spell and C is a calibration factor, in this study −4 and 4 were assigned for drought and wet. Finally, PDSI_{i-1} and Z_i from Eq. (A6) were added to compute the Sc-PDSI_i, using the p and q as weighting factors. The obtained values shown in Fig. A2 vary between 0.85 and 0.95 for p and 0.08 and 0.38 for q of a dry spell. These values are very important as they are to be used in the calculation of the moisture anomaly index needed to end (Z_e) and ameliorate (Z_a) a drought.

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References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration – Guidelines for computing crop water requirements, Irrig. Drain.e Paper 56, FAO, Rome, 1998.

Alley, W. M.: The Palmer drought severity index: limitations and applications, J. Appl. Meteorol., 23, 1100–1109, 1984.

Bartholy, J., Pongracz, R., and Sabitz, J.: Analysis of drought index trends for the Carpathian Basin using regional climate model simulations, EGU General Assembly, Vienna, Austria, 7–12 April 2013, EGU2013-6408, 2013.

Briffa, K. R., Jones, P. D., and Hulme, M.: Summer moisture variability across Europe, 1892–1991: an analysis based on the Palmer drought severity index, Int. J. Climatol., 14, 475–506, 1994.

Busuioc, A. and von Storch, H.: Changes in the winter precipitation in Romania and its relation to the large-scale circulation, Tellus A, 48, 538–552, doi:10.1034/j.1600-0870.1996.t01-3-00004.x, 1996.

Cheval, S., Busuioc, A., Dumitrescu, A., and Birsan, M. V.: Spatiotemporal Variability of the Meteorological Drought in Romania using the Standardized Precipitation Index, EGU General Assembly 2013, 7–12 April 2013, Vienna, Austria, id. EGU2013-7085, 2013.

Dai, A.: Characteristics and trends in various forms of the Palmer Drought Severity Index (PDSI) during 1900–2008, J. Geophys. Res., 116, D12115, doi:10.1029/2010JD015541, 2011.

Dai, A., Fung, I. Y., Del Genio, A. D., and Qian, T.: A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming, J. Hydrometeorol., 5, 1117–1130, 2004.

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Guttman, N. B.: Comparing the Palmer Drought Index and the standardized precipitation index, J. Am. Water Resour. As., 34, 113–121, 1998.
Guttman, N. B., Wallis, J. R., and Hosking, J. R. M.: Spatial comparability of the Palmer Drought Severity Index, Water Resour. Bull., 28, 1111–1119, 1992.
IPCC: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Summary for Policymakers Climate Change 2007: The Phisical Science Basis, available at: www.ipcc.ch, last access: 24 January 2014, 2007.
Karl, T. R.: Some spatial characteristics of drought duration in the United States, J. Clim. Appl. Meteorol., 22, 1356–1366, 1983.
Karl, T. R.: The sensitivity of the Palmer Drought Severity Index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration, J. Clim. Appl. Meteorol., 25, 77–86, 1986a.
Karl, T. R.: The relationship of soil moisture parameterizations to subsequent seasonal and monthly mean temperature in the United States, Mon. Weather Rev., 114, 675–686,1986b.
Karl, T. R. and Knight, R. W.: Atlas of monthly Palmer hydrological drought indices (1931–1983) for the contiguous United States, Natl. Clim. Data Cent., Asheville, NC, 7, 217 pp., 1985.
Karl, T. R., Knight, R. W., Ezell, D. S., and Quinlan, F. T.: Probabilities and precipitation required to end/ameliorate droughts, Historical Climatology Series 3-16, National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, 315 pp., 1986.
Karl, T. R., Quinlan, F., and Ezel, D. S.: Drought termination and amelioration: its climatological probability, J. Clim. Appl. Meteorol., 26, 1198–1209, 1987.
Lloyd-Hughes, B. and Saunders, M. A.: A drought climatology for Europe, Int. J. Climatol., 22, 1571–1592, 2002.
McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration of time scales, Eighth Conference on Applied Climatology, American Meteorological Society, 17–23 January, Anaheim CA, 179–186, 1993.
Oeztuerk, A.: On the study of a probability distribution for precipitation totals, J. Appl. Meteorol., 20, 1499–1505, 1981.
Palfai, I.: Description and forecasting of droughts in Hungary, in: Proc. of 14th Congress on Irrigation and Drainage (ICID), Rio de Janeiro, Brazil, 30 April–4 May 1990, 1-C, 151–158, 1990.

Palmer, W. C.: Meteorological Drought, US Department of commerce, Washington, D.C., Weather Bureau Research Paper 45, 58 pp., 1965.
Popova, Z., Kercheva, M., and Pereira, L. S.: Validation of the FAO methodology for computing ETo with limited data, Application to South Bulgaria, Irrig. Drain., 55, 201–215, 2006.
Spinoni, J., Antofie, T., Barbosa, P., Bihari, Z., Lakatos, M., Szalai, S., Szentimrey, T., and Vogt, J.: An overview of drought events in the Carpathian Region in 1961–2010, Adv. Sci. Res., 10, 21–32, doi:10.5194/asr-10-21-2013, 2013.
Szalai, S., Szinell, C. S., and Zoboki, J.: Drought monitoring in Hungary, in: Early Warning Systems for Drought Preparedness and Drought Management, World Meteorological Organization, Lisboa, 182–199, 2000.
Szinell, C., Bussay, A., and Szentimrey, T.: Drought tendencies in Hungary, Int. J. Climatol., 18, 1479–1491, 1998.
Thornthwaite, C. W.: An approach toward a rational classification of climate, Geogr. Rev., 38, 55–94, 1948.
Toth, G. and Weynants, M.: Multiscale thematic soil water database, Deliverable 4.4 of MyWater project (call: FP7-SPA.2010.1.1-04; contract No: 263188), Ispra, Italy, European Commission Joint Research Centre, IES, 2010.
Trnka, M., Dubrovský, M., Svoboda, M., Semerádová, D., Hayes, M., Žalud, Z., and Wilhite, D.: Developing a regional drought climatology for the Czech Republic, Int. J. Climatol., 29, 86–883, doi:10.1002/joc.1745, 2009.
UNEP/DEWA: Carpathian Environment Outlook (KEO) Report 2007, Genève, 2007.
van der Schrier, G., Briffa, K. R., Jones, P. D., and Osborn, T. J.: Summer moisture variability across Europe, J. Climate, 19, 2818–2834, doi:10.1175/JCLI3734.1, 2006a.
Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., Angulo, M., and El Kenawy, A.: A new global 0.5° gridded dataset (1901–2006) of a multiscalar drought index: comparison with current drought index datasets based on the Palmer Drought Severity Index, J. Hydrometeorol., 11, 1033–1043, doi:10.1175/2010JHM1224.1, 2010b.
Wells, N., Goddard, S., and Hayes, M. J.: A self-calibrating Palmer Drought Severity Index, J. Climate, 17, 2335–2351, 2004.
Wilhite, D. A.: Drought as a natural hazard: concepts and definitions, in: Drought: a Global Assessment, vol. 1, edited by: Wilhite, D. A., Routledge, New York, 1–18, 2000a.

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Wilhite, D. A. and Buchanan, M.: Drought as hazard: understanding the natural and social context, in: Drought and Water Crisis: Science, Technology, and Management Issues, edited by: Wilhite, D. A., CRC Press (Taylor and Francis), New York, 3–29, 2005.
Wösten, J. H. M., Lilly, A., Nemes, A., and Le Bas, C.: Development and use of a database of hydraulic properties of European soils, Geoderma, 90, 169–185, 1999.
WMO/UNCCD/FAO/UNW-DPC: Capacity Development to Support National Drought Management Policies initiative, available at: http://www.ais.unwater.org/ais/course/view.php?id=37 (last access: 29 November 2013), 2013.

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Table 1. Cumulative frequency, severity classes, and SC-PDSI values in the Carpathian region.

Cumulative frequency (%)	Severity classes	Sc-PDSI value
2.4	Extremely wet	4 or more
4.1	Severe wet	3.00–3.99
7.4	Moderately wet	2.00–2.99
11.6	Slightly wet	1.00–1.99
7.2	Incipient wet spell	0.50–0.99
17.3	Near normal	0.49 to −0.49
9.1	Incipient dry spell	−0.50 to −0.99
16.7	Slightly dry	−1.00 to −1.99
12.5	Moderately dry	−2.00 to −2.99
7.6	Severely dry	−3.00 to −3.99
4.0	Extremely dry	−4 or less

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Table 2. Percentage above the normal of precipitation needed to end a drought – P_p (%) – in the next 1, 3, 6 months for the drought events with the highest incidence (% surface from the region).

Years	2003	1990	1990	2003	1986	2003	1990	1990	1991	1990
Month	8	8	7	9	12	6	9	6	3	10
Incidence (%)	93.3	92.6	88.5	88.1	85.8	85.6	85.5	84.7	83.9	83.9
1 month P_p (%)	414.5	376.9	625.1	204.1	368	228.2	415.7	374.3	462.5	482.3
3 month P_p (%)	195.7	230.8	160.9	172.5	110.7	129.7	360.3	118.7	99	233.3
6 month P_p (%)	25.2	57.9	52	21	36.3	34.3	63.1	49.2	48.2	62.3

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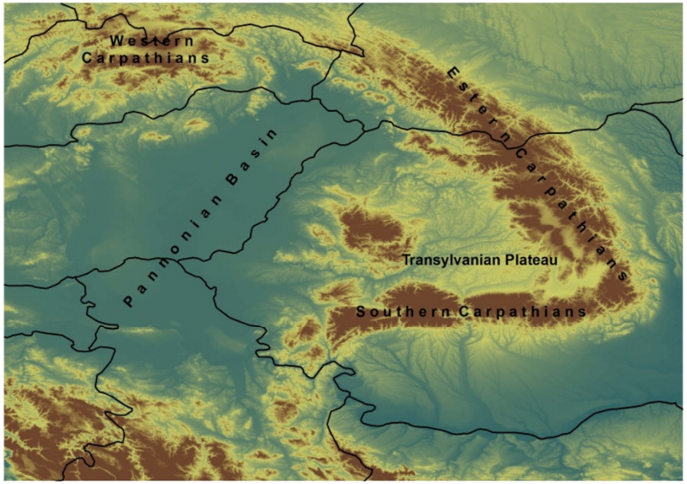

Fig. 1. Carpathian region – geographical units.

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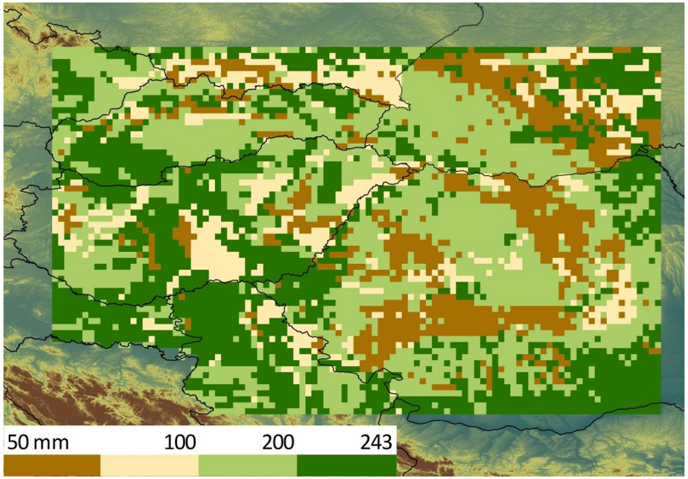

Fig. 2. Available Water Holding Capacity (AWC) of the soil (mm) in the Carpathian region.

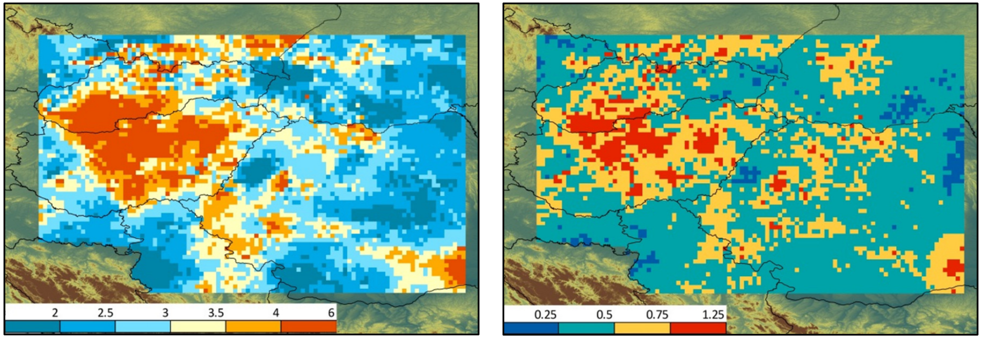

Fig. 3. Average number of months per year with moderate drought (Sc-PDSI ≤ -2.0) (left) and extreme drought (Sc-PDSI ≤ -4.0) (right) in the Carpathian region (1961–2010).

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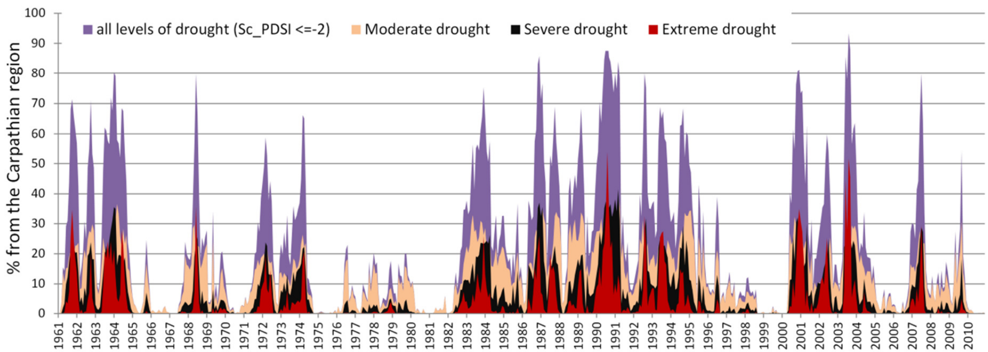

Fig. 4. Incidence (% surface of the region) of different severity levels of drought per month.

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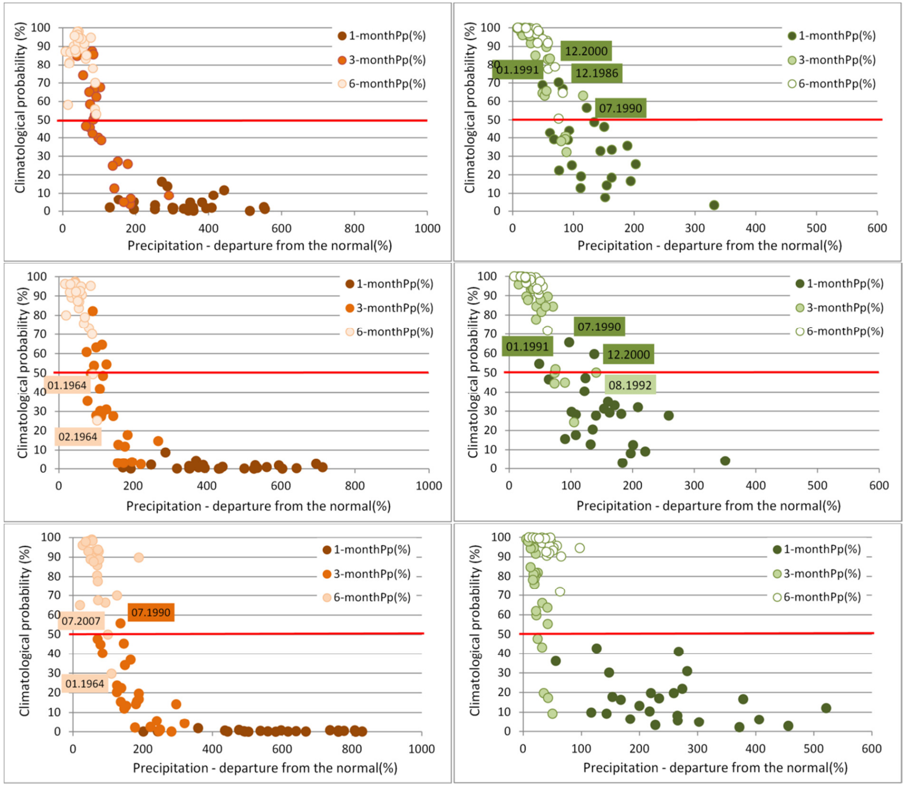

Fig. 5. Probability (%) of ending (left) or ameliorating (right) moderate (top), severe (centre) and extreme drought (bottom) events with the highest incidence in the Carpathian region in the next 1, 3, 6 months.

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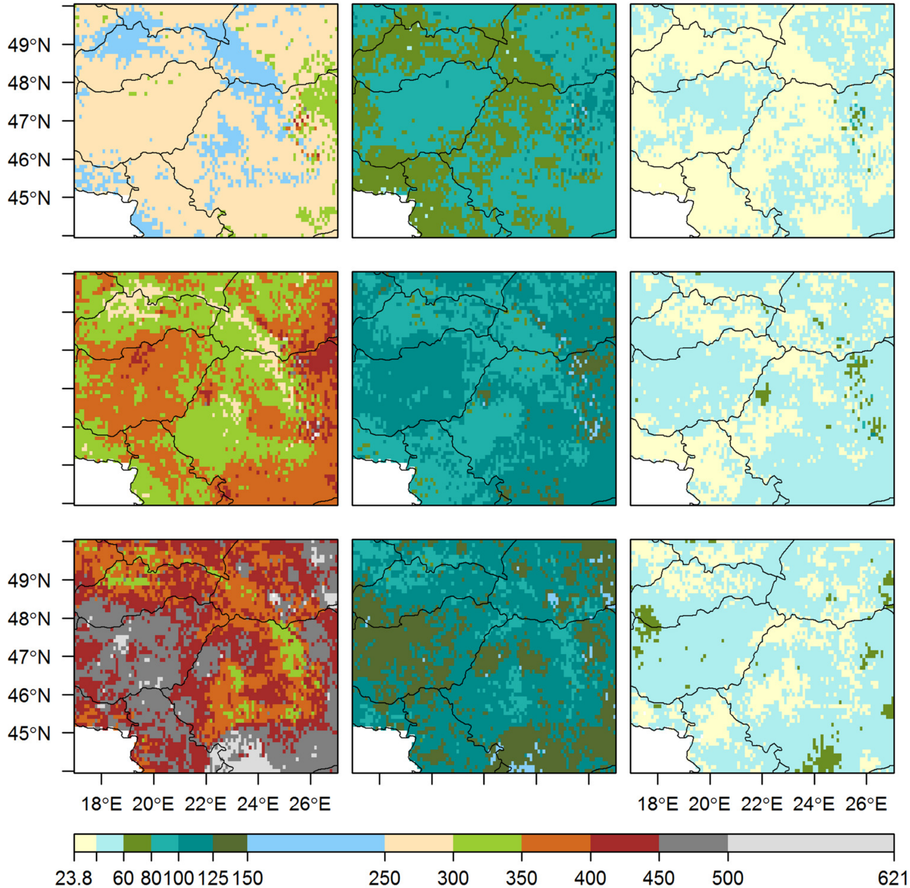

Fig. 6. Percentage (%) above the normal of precipitation needed to end a (top) moderate ($-3 < \text{Sc-PDSI} \leq -2$), (centre) severe ($-4 < \text{Sc-PDSI} \leq -3$) and (bottom) extreme drought ($\text{SC-PDSI} \leq -4$) in the next month (left), next 3 months (centre) and next 6 months (right) (1961–2010).

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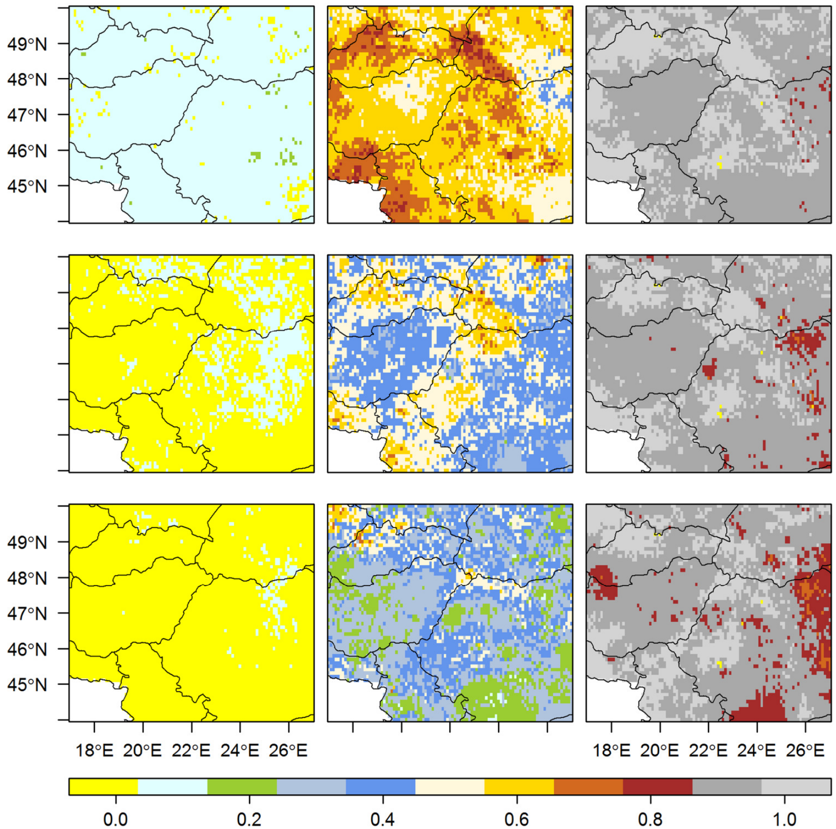

Fig. 7. Climatological probability (%) of receiving the precipitation needed to end a (top) moderate ($-3 < \text{Sc-PDSI} \leq -2$), (centre) severe ($-4 < \text{Sc-PDSI} \leq -3$) and (bottom) extreme drought ($\text{SC-PDSI} \leq -4$) in the next month (left), next 3 months (centre) and next 6 months (right) (1961–2010).

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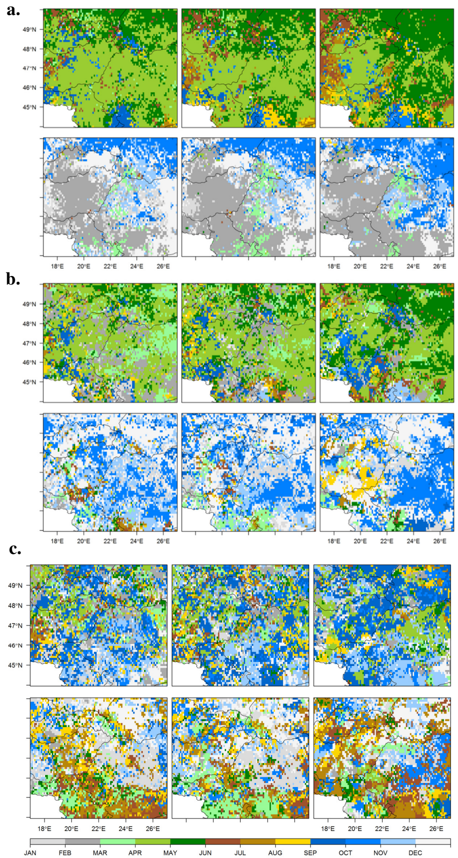

Fig. 8. The months with the highest (top), and lowest (bottom) probability of having (left) a moderate drought ($-3 < \text{Sc-PDSI} \leq -2$), (centre) severe ($-4 < \text{Sc-PDSI} \leq -3$) and (right) extreme drought ($-4 \leq \text{Sc-PDSI}$) terminated in **(a)** the next month, **(b)** the next 3 months and **(c)** the next 6 months.

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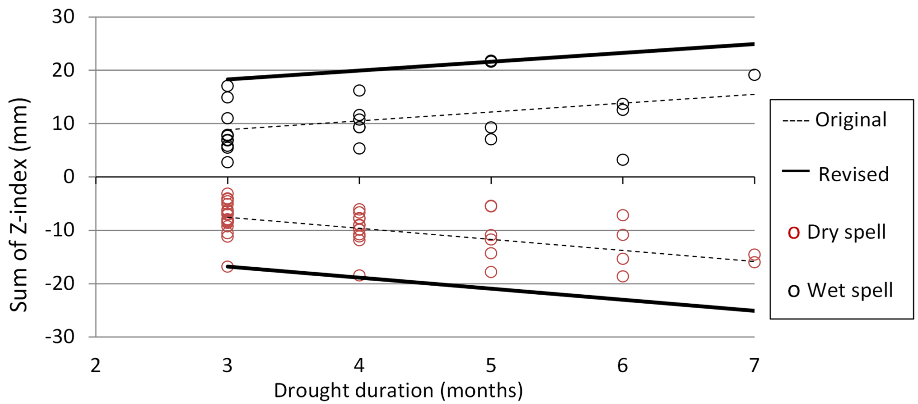

Fig. A1. Accumulated Z-index (mm) vs. duration (months) with the intercept of the most extreme drought/wet spell.

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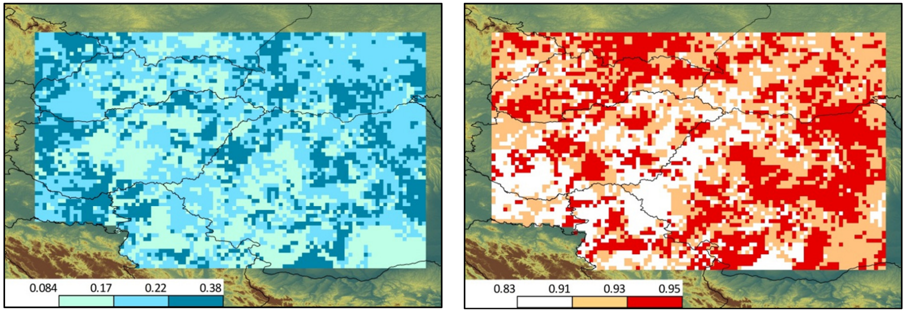

Fig. A2. Duration factors p (left) and q (right) for dry cases in the Carpathian region (1961–2010).